

Is Heavy Quark Axion Necessarily Hadronic Axion?

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Abstract

We show that heavy quark axion is not necessarily a hadronic axion, which manifests in the quark and lepton seesaw mechanism. We introduce a heavy $SU(2)$ singlet fermion for each known fermion in order to unify the axion scale and the seesaw scale. The light quarks and leptons gain their masses by the seesaw mechanism. Even though our axion model gives a kind of heavy quark axion, the axion has tree level lepton–axion coupling suppressed by F_a , contrary to a widely known belief that heavy quark axions are hadronic.

θ_{QCD} is one of twenty parameters of the standard model which is expected to be explicable in a satisfactory theory, which is the well-known strong CP problem. Axion is the most attractive solution for the strong CP problem [1, 2]. At present there exist two viable axion models. One is the heavy quark axion [3] and the other is the Dine–Fischler–Srednicki–Zhitnicky (DFSZ) axion [4]. Usually heavy quark axion is referred to as hadronic axion because the heavy quark axion has no tree level coupling with the leptons. For the DFSZ model there exists the lepton–axion couplings of order m_l/F_a . Except for this lepton couplings, the heavy quark axion and the DFSZ axion models have hadronic couplings of the same order. Thus most phenomenological and astrophysical consequences of these two models are similar¹. The invisible axion lifetime is much larger than the age of the universe, and hence the classical axion field can contribute to the mass density of the universe significantly. This consideration gives a bound on the axion decay constant, $F_a \leq 10^{12}$ GeV; $F_a \sim 10^{12}$ GeV can supply cold axions as the needed cold dark matter.

In the standard model, neutrinos are massless. However, the solar neutrino problem invites a speculation for tiny neutrino masses, $\Delta m_\nu \sim \mathcal{O}(\text{eV})$. An attractive suggestion for this tiny mass is the so-called seesaw mechanism [6], by introducing $SU(2) \times U(1)$ singlet(s) at an intermediate scale $10^{10\text{--}15}$ GeV.

The two scales encountered above falls in the common region; $10^{10} - 10^{13}$ GeV². This common scale appears in supergravity models also [8]. Therefore, it is quite intriguing to speculate that the axion scale and the seesaw scale arise from the same origin. In fact, it is easy to relate these two scales in grand unified models [9]. If the symmetry of the grand unification group G is $G \times U(1)_{PQ}$, the Peccei–Quinn symmetry breaking scale F_a is the axion scale. If G breaks down to the standard model gauge

¹Actually, there has been several arguments about cosmological difference between the DFSZ and the hadronic axion[2, 5].

²We extended the upper bound of axion scale a bit, because there exists a possibility of raising it as noted in the saxino cosmology[7].

group at the grand unification scale M_X , there may exist some $SU(3) \times SU(2) \times U(1)$ singlets which remain massless at M_X , protected by $U(1)_{PQ}$. These singlets can obtain masses when the Peccei–Quinn symmetry is broken at the axion scale; thus the axion scale becomes the seesaw scale, and the Chikashige–Mohapatra–Peccei majoron[10] is the same as the invisible axion.

Existing models which try to unify these two scales are based on the DFSZ axion model; two Higgs doublet and one singlet scalar [9, 10] are introduced at the level of the standard model.

In this paper, we study the unification of these two mass scales in the framework of the heavy quark axion model. Namely, instead of introducing a new Higgs doublet, we introduce a heavy singlet quark which couples to the same singlet scalar as singlet right-handed neutrino in the seesaw model. Thus there exists only one Higgs doublet at low energy. We can set a universal model for solving the strong CP problem and the solar neutrino puzzle based on the heavy quark axion model. To make a consistent model, we need to introduce a heavy singlet partner to each lepton. In grand unified theory (GUT), we encounter frequently heavy $SU(2) \times U(1)$ singlet fermions below the GUT scale. [In superstring standard models, these singlet leptons and quarks are almost inevitable [11].] If heavy leptons arise as singlets below the GUT scale, there may exits heavy $SU(2) \times U(1)$ singlet quarks also [11]. So it is not unreasonable to assume that all light fermions have their heavy singlet partners and get their masses by the seesaw mechanism only. At low energy scale, phenomenology of the quark sector seesaw model is the same as the standard model except for the axionic interactions. This axion is an invisible heavy quark axion but *not* hadronic axion. And the quark axion interaction in this model is different from that of the hadronic axion. This illustrates that the heavy quark axion model is not necessarily a hadronic axion, which makes it more difficult to rule out heavy quark axions by finding out axion–electron coupling. On the other hand, it is a good news for experiments; more

invisible axion models have electron couplings, and probing the electron coupling in the axion search experiments applies to wider classes of models.

In addition to the familiar quarks and leptons in the standard model, we postulate new $SU(2)$ singlet fermions and one complex scalar σ [2]. The fermion contents of the model is,

$$\begin{aligned} \text{in the quark sector} &: q_L^i, u_R^i, d_R^i, U_L^i, U_R^i, D_L^i, D_R^i, \\ \text{in the lepton sector} &: l_L^i, e_R^i, N_R^i, E_L^i, E_R^i, \end{aligned} \quad (1.a)$$

and an extra heavy quark to realize the heavy quark axion,

$$Q_L, Q_R, \quad (1.b)$$

where $i = 1, 2, 3$ is a family index. q_L^i and l_L^i are $SU(2)$ doublets, and the other fields are $SU(2)$ singlets. Extra particles added to the standard model are denoted as capital letters. Their electromagnetic charges are the same as those of the corresponding light particles (lower case symbols) but the electromagnetic charge of Q is undetermined. We assign PQ charges to fermions as,

$$\begin{aligned} 1 &\text{ for } Q_R, U_R, D_R, E_R, N_R, q_L, l_L, \\ -1 &\text{ for } Q_L, U_L, D_L, E_L, u_R, d_R, e_R, \\ 0 &\text{ for } H, \\ -2 &\text{ for } \sigma. \end{aligned} \quad (2)$$

Note that the Higgs doublet carries vanishing PQ charge.

Then the Lagrangian can be written as

$$\begin{aligned} \mathcal{L} = & b_\sigma \sigma \bar{Q}_L Q_R + b_U \sigma \bar{U}_L U_R + b_D \sigma \bar{D}_L D_R + b_E \sigma \bar{E}_L E_R + \frac{1}{2} b_N \sigma \bar{N}_R^c N_R \\ & + h_U \bar{q}_L \tilde{H} U_R + h_D \bar{q}_L H D_R + h_N \bar{l}_L \tilde{H} N_R + h_E \bar{l}_L H E_R \\ & + \alpha_U \bar{U}_L u_R + \alpha_D \bar{D}_L d_R + \alpha_E \bar{E}_L e_R + \text{h.c.} \\ & - V(\sigma, H) + \mathcal{L}_{kinetic} + \mathcal{L}_{gauge}, \end{aligned} \quad (3)$$

where H is a Higgs doublet scalar, $\tilde{H} = i\sigma_2 H^*$, b_N is a Hermitian matrix while the other coupling matrices are complex, and

$$V(\sigma, H) = \mu_H^2 H^\dagger H + \mu_\sigma^2 \sigma^* \sigma + \lambda_H (H^\dagger H)^2 + \lambda_\sigma (\sigma^* \sigma)^2 + \lambda_{\sigma H} H^\dagger H \sigma^* \sigma. \quad (4)$$

After the spontaneous symmetry breaking, one has

$$\sigma = \frac{\tilde{v} + \tilde{\rho}}{\sqrt{2}} e^{ia/\tilde{v}}, \quad H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \rho \end{pmatrix} e^{i\phi/v}. \quad (5)$$

Here \tilde{v} is the Peccei–Quinn symmetry breaking scale and v is the weak scale. The tree level mass matrix of fermions except for neutrinos written in the $(f^1, f^2, f^3, F^1, F^2, F^3)_L \otimes (f^1, f^2, f^3, F^1, F^2, F^3)_R$ space is³

$$M_f = \begin{pmatrix} 0 & h_F v \\ \alpha_F & b_F \tilde{v} \end{pmatrix}, \quad (6)$$

where b , h , α are 3×3 matrices and f and F represent approximately light and heavy fermions, respectively. To simplify further analysis, assume b_F and α_F are diagonal so that h_F can be diagonalized by biunitary transformation. Namely, we are neglecting the mixing angles. If one of the three matrices, α_F , b_F and h_F , is diagonal, the mixing can be introduced in general. So we can separate single family mass matrix

$$M_f^i = \begin{pmatrix} 0 & h_F^i v \\ \alpha_F^i & b_F^i \tilde{v} \end{pmatrix}, \quad (7)$$

where $i = 1$ or 2 or 3 . Above matrices can be diagonalized to

$$M_f^{Di} = \begin{pmatrix} m^i & 0 \\ 0 & M^i \end{pmatrix} \simeq \begin{pmatrix} h_F^i v \alpha_F^i / b_F^i \tilde{v} & 0 \\ 0 & b_F^i \tilde{v} \end{pmatrix}, \quad (8)$$

where M^i represents heavy fermion masses. Since the mass parameter α_F can be of order \tilde{v} , the light fermion masses are of order $v \times$ (coupling constants). We note that the large ratio of Yukawa couplings f_t/f_u in the standard model can be distributed to

³There are three such matrices, for $Q_{em} = 0, 2/3, -1/3$, respectively.

two classes of couplings h_F^i and α_F^i , and hence lessening the fermion mass hierarchy problem. Now, we can represent fermions as mass eigenstates f' and F'

$$\begin{aligned} f_L &\simeq f'_L + \frac{h_F^* v}{b_F \tilde{v}} F'_L, \quad F_L \simeq F'_L - \frac{h_F v}{b_F \tilde{v}} f'_L \\ f_R &\simeq f'_R + \frac{\alpha_F^*}{b_F \tilde{v}} F'_R, \quad F_R \simeq F'_R - \frac{\alpha_F}{b_F \tilde{v}} f'_R. \end{aligned} \quad (9)$$

So, all light fermions f' acquire their masses through the seesaw mechanism. For the neutrinos, the mass matrix can be written in $(\nu_L, N_R) \otimes (\nu_L, N_R)$ basis,

$$M_N = \begin{pmatrix} 0 & h_N v \\ h_N^* v & b_N \tilde{v} \end{pmatrix}, \quad (10)$$

Diagonalizing its mass matrix, a light neutrino acquires its mass $m_\nu \simeq |h_N v|^2/M_N$ which is very small. For light neutrinos, there do not exist the α couplings present in e, u and d fermions; thus neutrinos do not have mass at order v .

Axion effective interaction $a/(32\pi^2 \tilde{v}) F \tilde{F}$ term comes from the heavy singlet quark Q , which has no light partner. The PQ current of the lagrangian (2) is

$$\begin{aligned} J_\mu^{PQ} &= \tilde{v} \partial_\mu a - \frac{1}{2} \left(\bar{Q} \gamma_\mu \gamma_5 Q + \sum_{i=1}^3 [\bar{U}^i \gamma_\mu \gamma_5 U^i + \bar{D}^i \gamma_\mu \gamma_5 D^i + \bar{E}^i \gamma_\mu \gamma_5 E^i \right. \\ &\quad \left. - \bar{u}^i \gamma_\mu \gamma_5 u^i - \bar{d}^i \gamma_\mu \gamma_5 d^i - \bar{e}^i \gamma_\mu \gamma_5 e^i] \right). \end{aligned} \quad (11)$$

The divergence of J_μ^{PQ} has the anomaly term only

$$\partial^\mu J_\mu^{PQ} = -\frac{a}{32\pi^2 \tilde{v}} F_{\mu\nu}^a \tilde{F}^{a\mu\nu}. \quad (12)$$

If it were not for the anomaly term, a would be massless. To remove the anomaly term, a proper axion current is defined as,

$$J_\mu^a = J_\mu^{PQ} + \frac{1}{2(1+Z)} (\bar{u} \gamma_\mu \gamma_5 u + Z \bar{d} \gamma_\mu \gamma_5 d), \quad (13)$$

where $Z = m_u/m_d$ and we neglect heavier quarks. In the diagonalized basis, the axion does not mix with π^0 and J_μ^a has a divergence

$$\partial^\mu J_\mu^a = \frac{im_u}{1+Z} (\bar{u} \gamma_5 u + \bar{d} \gamma_5 d). \quad (14)$$

Thus the axion mass is estimated as

$$m_a = \frac{f_\pi m_{\pi^0}}{\tilde{v}} \frac{\sqrt{Z}}{1+Z}, \quad (15)$$

which is the same as that of the original heavy quark axion model. However, the couplings between axion and matter fields are rather different. For the original model, the heavy quark axion couples to the light quarks with the same strength [2]. But, this new heavy quark axion has different couplings between u and d quarks,

$$\begin{aligned} \langle \beta, a | \mathcal{L} | \alpha \rangle &= \frac{-i}{\tilde{v}} \langle \beta | [Q_5^a, \mathcal{L}] | \alpha \rangle \\ &\simeq im_u \frac{2+Z}{1+Z} \langle \beta | \bar{u} \gamma_5 u | \alpha \rangle + im_d \frac{1+2Z}{1+Z} \langle \beta | \bar{d} \gamma_5 d | \alpha \rangle. \end{aligned} \quad (16)$$

For the leptonic sector, the original heavy quark axion has no tree level axion lepton coupling, and arises at one loop order. In this new model, below symmetry breaking scale, we have tree level lepton-axion coupling,

$$\mathcal{L}_{lla} = \frac{ia}{\sqrt{2}} \frac{m_e}{\tilde{v}} \bar{e}^i \gamma_5 e^i. \quad (17)$$

Couplings	DFSZ axion	Hadronic axion	New heavy quark axion
$c_{a\gamma\gamma}$	0.75	$q^2 - 1.92$	$q^2 - 1.92$
g_{aee}	$1.4 \times 10^{-11} X_d \left(\frac{3}{N_g} \right) \left(\frac{m_a}{\text{eV}} \right)$	~ 0	$5.8 \times 10^{-11} \left(\frac{m_a}{\text{eV}} \right)$

Table 1: Photon–axion, electron–axion couplings [2]. Here $Z = 0.56$, and electromagnetic charge of Q is defined as qe .

In this paper, we have explored the consequences of new heavy quark axion model. The main idea of this model is to combine the two different scales, the axion decay constant and the right-handed neutrino mass in the seesaw model. Our model is a simple extension of the standard model by doubling the number of fermions and with

additional $U(1)_{PQ}$ symmetry. It is consistent with the existing experimental data, since below the electroweak scale it reproduces the standard model except for the very light majorana neutrinos which solve the solar neutrino puzzle and the invisible axion which solves the strong CP problem. In contrast to the original heavy quark axion, new heavy quark axion has tree level axion lepton coupling term and different coupling strengths between u and d quarks. It will be interesting to see if our model can be extended to a GUT. More careful experiments are required to distinguish the two Higgs doublet axion model and the one Higgs doublet axion model (the heavy quark axion model).

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